

Human Research Program (HRP)

Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions

Subject Matter Expert Consensus Session Report

Net Habitable Volume Number Charge. In the spring of 2013, the NASA Human Research Program (HRP) charged the Behavioral Health and Performance (BHP) Element with the task of defining a minimum net habitable volume (NHV)—that is, a minimum number of cubic meters/feet – needed to support crews for exploration missions. Such missions involve travel at greater distances, beyond low-Earth orbit, and could consist of longer durations (up to 2.5 years, or approximately 912 days) than current 6-month International Space Station (ISS) missions.

Subject Matter Experts Consensus Session. Toward this goal, a NASA-based NHV Team consisting of representatives from several HRP Elements (Behavioral Health and Performance, Space Human Factors and Habitability, Exploration Medical Capability) and Exploration Habitation, planned and implemented an evidence-based consensus session with a selected group of subject matter experts (SMEs), to derive a minimum acceptable NHV number for a Mars mission. The session included a panel of 5 external SMEs with relevant backgrounds in psychology (behavioral, cognitive, and environmental), architecture, and industrial ergonomics. A detailed list of the participants can be found in Appendix 1. The SME consensus session was held January 22 and 23, 2014 at the NASA Johnson Space Center, with 2 of the 5 SMEs participating virtually.

Considerations. Before deliberations, representatives from the NASA-based NHV Team provided background materials to the SMEs and discussed relevant items to assist in deriving the minimum acceptable NHV. These items were:

Definition of Net Habitable Volume: The definition of functional volume is “...the volume left available to the crew after accounting for the loss of volume due to deployed equipment, stowage, trash, and any other structural inefficiencies and gaps (nooks and crannies) that decrease the functional volume” (HIDH, 2010).

Definition of Minimum Acceptable Net Habitable Volume: For the purpose of the consensus session, a definition for Minimum Acceptable NHV, was established: “the minimum volume of a habitat that is required to assure mission success during exploration-type space missions with

prolonged periods of confinement and isolation in a harsh environment. This definition acknowledges that, in theory, smaller volumes are possible; however, these would be unacceptable from human factors and behavioral health perspectives with likely negative consequences for psychosocial well-being and performance of the crew and thus mission success. The minimum acceptable NHV depends on multiple parameters, including crew size, mission duration, and functional-task requirements – while considering the volume required for crew to perform necessary tasks and maintain psychological and behavioral well-being. In this instance, considerations in defining minimal acceptable volume included volume requirements for relevant task envelopes, as well as volume-related requirements associated with maintaining psychological and behavioral health over extended durations (for example, 1 to 2.5-year missions), while living and working in an isolated, confined spacecraft environment in deep space.”

Exploration Mission Parameters. For the purpose of defining a minimum acceptable NHV number and associated caveats, mission parameters based on the NASA Mars Design Reference Architecture 5.0 (Drake, 2009), were defined. Panelists and NASA representatives were asked to determine a minimum acceptable NHV number for a mission that provided the following characteristics:

Total Mission Duration	30 Months
- In transit to	6 months
- At target	18 months
- In transit from	6 months
Crew Size	N = 6
Crew Composition	Pilot, Physician, Geologist, Biologist, Engineer, Electrical Engineer
Gender Mix	Variable; exact mix undefined
Cultural Mix	Presumably some combination of US, Russia, Europe, Canada and Japan
Mission Tempo	Long periods of low mission tempo, interspersed with high activity times (for example, launch, jettison tanks, dock, landing)
Communication Delays	Up to 22 minutes one-way with blackout periods
Autonomy from Ground	Increasing en route to Mars, decreasing during return to Earth

Consensus Session Objectives. The 5 SMEs were asked to provide inputs to the following objectives of the NHV consensus session:

1. Provide a minimal acceptable NHV number based on the best available evidence from your field and spaceflight constraints given to you by NASA

2. Define the dependencies of the number based on caveats and countermeasure scenarios
3. Determine how minimal acceptable NHV volume changes with duration

Minimum Acceptable Net Habitable Volume

Based on the characteristics and parameters of the exploration class mission defined in Mars DRM 5.0 (Drake, 2009), the SMEs, with concurrence of the NASA representatives, recommended a minimum acceptable NHV of 25 m³ (883 ft³) per person.

Approach: The recommended minimal acceptable volume was derived through a series of steps, starting with the identification of tasks (hygiene, exercise) that are expected to occur on a long-duration mission. Based on prior work conducted by the NASA Space Human Factors and Habitability Element, the minimum volume needed for conducting such tasks was identified (Human Integration Design Handbook, 2010, <http://ston.jsc.nasa.gov/collections/trs/techrep/SP-2010-3407.pdf>).

Discussions were held regarding the co-location of relevant tasks; for example, the ability to conduct medical evaluations in the private crew quarters. While such an effort to identify specific overlaps had been previously accomplished (Thaxton, Chen, & Whitmore, 2013), the current effort entailed 'grouping' like-tasks into functional areas and then using specific task-based volume numbers to determine the volume needed for that multi-functional area. Hence, the key functions of a crew on a Mars mission were mapped to physical locations needed on a vehicle.

Overall, 7 functional areas were identified:

1. Berthing, or sleeping space/private quarters
2. Dining and communal activities
3. Work space
4. Exercise (area can also accommodate EVA suit donning and medical care)
5. Hygiene
6. Translation portals or pass-throughs
7. Stowage access

Caveats. The minimum acceptable NHV recommendation is based on the following caveats (additional caveats specific to each functional area are listed in the subsequent section):

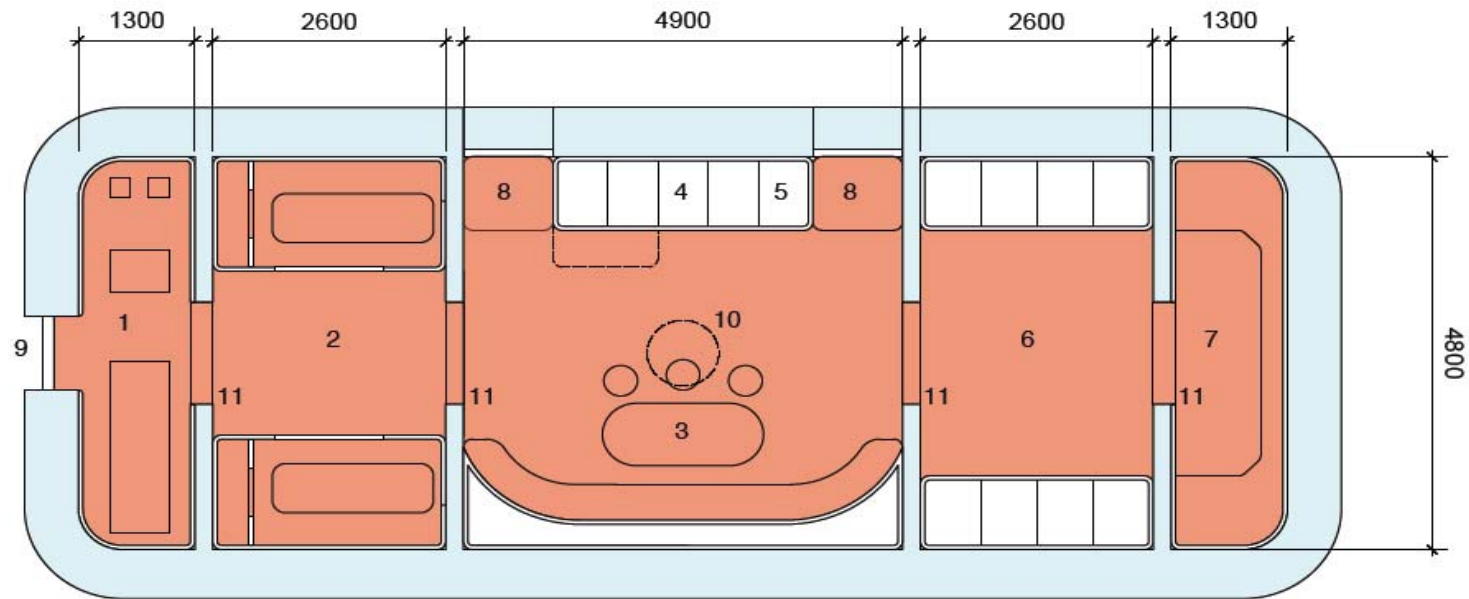
- Careful consideration was given towards determining the needed volume to support each functional area and the relative location of these functional areas. Thus, the recommended

overall minimal volume should only be considered “acceptable” in the context of these design and volume requirements specific to each area, and the overall minimal volume therefore may no longer be acceptable if volume were to be subtracted from one functional area to enhance the volume of another

- A microgravity environment that allows use of all of the volume
- A separate radiation shelter is not accounted for within the defined minimum acceptable NHV number because it is assumed the crew habitat vehicle will offer appropriate radiation shielding
- The proposed volume takes into account suit donning and doffing for EVAs, but additional volume may be needed to adequately address other EVA requirements (air lock). If so, the definition of this requirement will occur at another time
- Assumes crew of 6; if crew number decreases, the volume per crewmember may increase as the relationship between crew size and acceptable volume requirements for areas such as dining and communal, exercise, and hygiene is not assumed to be linear
- A larger volume for crew quarters than has existed in past spaceflight missions, to provide privacy and restoration that will be needed in the long-duration exploration mission owing to the increased period of isolation and confinement
- Point-of-use stowage is included in all areas
- Rational layout of areas to allow for a separation of quiet and loud activities, as well as clean and dirty activities
- Acoustic isolation and privacy between disparate activities/spaces
- Within the spaces, acoustics are provided at appropriate levels and sound attenuation built-in
- Ability for crew to optimize aesthetics and personal control over environment (for example, allowing for flexible lighting and other aspects of the environment to be modifiable and flexible), and functional configuration so areas are ergonomic and rational
- Assumes adequate sensory stimulation related to touch, sounds, smells, and vision

The proposed habitat that meets the defined minimum acceptable NHV number and the locations of the 7 functional areas are shown in Figures 1 and 2 below. (The architectural sketches were developed by Hugh Broughton Architects, one of the SMEs.)

Figure 1. Functional Areas and Volumes Within Habitat



Key

- 1 Exercise space and EVA suit don/doff area
- 2 6 berths of 5.43m³ each
- 3 Recreation with hydraulic table and stools
- 4 Galley
- 5 Hydroponics integral to galley
- 6 Laboratories and work space
- 7 Hygiene
- 8 Access to stowage
- 9 Hatch
- 10 Window seat above
- 11 Bulkheads define zones

Volumes

Berthing	42.36m ³
Recreation/dining	49.95m ³
Workspace	21.29m ³
Exercise	17.55m ³
Hygiene	17.55m ³
Bulkheads	1.30m ³
TOTAL	150.00m³

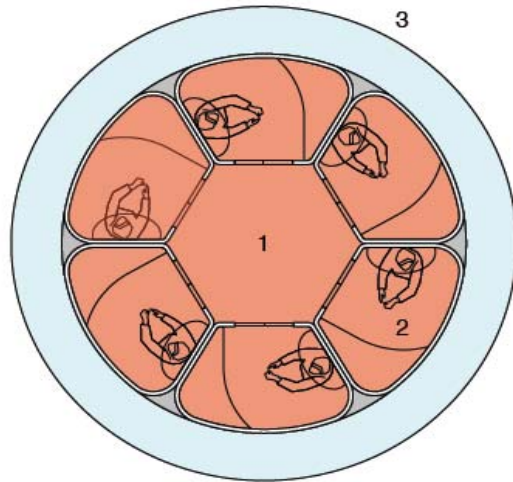
Net Habitable Volume

6 person crew	150m ³ / 6
per person	25m ³

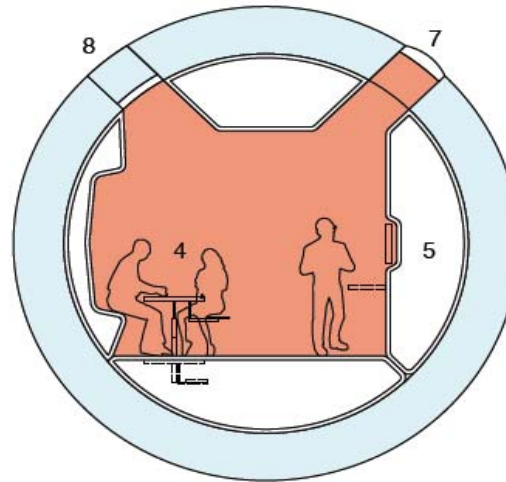
**NASA net habitable volume consensus
Volume calculation exercise**

Hugh Broughton Architects
February 2014

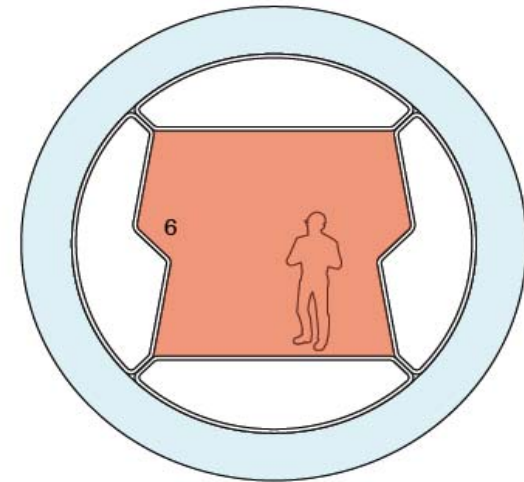
Figure 2. Detailed View of Berthing, Dining and Workspace Functional Areas Inside Habitat for Exploration Class Missions



Berthing section
Sectional area = 16.21m²



Dining section
Sectional area = 10.45m²



Work section
Sectional area = 8.12m²

Key

- 1 Circulation space 2m wide
- 2 6 berths of 5.43m³ each
- 3 Stowage etc around perimeter
- 4 Dining/recreation with hydraulic table and stools
- 5 Galley
- 6 Laboratories and work space
- 7 Window
- 8 Access to stowage

**NASA net habitable volume consensus
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Caveats Specific to Functional Areas. The following caveats apply to specific functional areas as identified below.

Berthing, or sleeping space private, crew quarters (Areas 1 and 2 in Figure 2)

- Individual private quarters are to be provided for each crewmember
- The volume for each individual crew quarters is **5.4 m³ (190.70 ft³)**
 - These have been sized to allow crewmembers individual personal space for sleep, self-care (hygiene), and recreation, also acknowledging that adequate personal space becomes even more important in missions of such unprecedented duration (Simon, Whitmire, & Otto, 2012)
 - ISS crew quarters are, by comparison, 2.1 m³ (74 ft³). The size of individual quarters also allows for temporary isolation of a sick crewmember
- Quarters are clustered together to provide for alternative social space
 - Allows for acoustic and vibration isolation from the remainder of the vehicle
 - Acoustic isolation to protect sleep and private communication
 - Can allow space for medical care (as can the Exercise area)
- Multi-purpose access space (Area 1 in Figure 2) allows for simultaneous crewmember access to crew quarters as well as suited egress through that area
- Quarters can be personalized (e.g. hanging pictures, varying positioning of bedding)

Dining and Communal Activities (Areas 3 and 10 in Figure 1, Area 4 in Figure 2)

- The Dining and Communal Activities area is designed to support communal activities, foster team cohesion, and provide space for team recreation and other important countermeasures for psychological health
- Minimal volume assumes sufficiently large space to simultaneously fit all 6 crewmembers, so that all 6 can dine together, as well as sit together to view video or participate in a team event
- Flexible space to allow for both dining and communal activity
 - Differing orientations achieved in microgravity supports multiple tasks
- Includes a window with a portal (~ 0.5 m³ [1.7 ft³]) as a way to visually extend the social space and provide an important countermeasure for psychological health

- Includes space/functionality and flexibility for a large screen (that may be comprised of smaller screens tiled together and may be removable rather than permanent) to be used for virtual window views, training/planning purposes, and screen-based recreation
- Includes sufficient space that is readily accessible for food preparation and storage
- Includes a minimal plant growth chamber that will provide countermeasure support for psychological health while providing multi-sensory stimulation
- Stowage access and access to window serves as form of definition/divider between areas of different activity without impeding sense of volume
- Table flexibility (e.g., can be stowed) to allow for increased space as needed

Stowage (Area 3 in Figure 2) and Stowage Access (Area 8 in Figure 1 and 2)

- Logistics are assumed to be stored outside of the habitable area to provide additional radiation protection
- Size and volume driven by optimizing efficiency related to accessing stowed materials
- Location is utilized to improve acoustic isolation
 - Stowage at two locations to improve accessibility and minimize crew time (between berthing and galley, and between galley and the workspace)

Workspace (Area 6 in Figure 2)

- Sized to allow up to 4 crewmembers to focus on meaningful work or activities simultaneously
- Separated from the Dining and Communal Area to avoid cross-contamination
- Design of area is task-driven

Exercise (Area 1 in Figure 1)

- Allows for 2 exercise devices to be used concurrently
- Assumes exercise equipment will be smaller than what is currently being used on ISS
- Assumes medical activities can occupy the same space with a pause on exercise equipment during that period
- Separated from dining area
- Equipment can be stowed and portable
- If possible, redundancy of exercise equipment – parts can be shared between exercise devices

- Includes window with viewing area to support mission activities when external views are required and offer an important psychological countermeasure

Hygiene (Area 7 in Figure 1)

- Provide volume for at least 2 separated hygiene and waste compartment areas
- Located away from berthing and galley for privacy and olfactory separation, although distance from sleeping quarters (particularly at night) should be considered
- Assumes some self-care/hygiene tasks can also be completed in crew quarters

Translation Portals, or Pass-through

- Function-thin partitions for visual and acoustic separation
- Assumes additional volumes for pass-throughs and transition paths
- Adequately sized for a suited crewmember

Mission Duration. The third objective of the SME consensus session sought to characterize how minimal acceptable NHV changes with mission duration. The consensus recommendation was: **Given that the volume is defined by the functions required of the mission, reducing the volume to accommodate a shorter mission is not recommended.** The proposed volume of 25 m³ (883 ft³) is consistent with previously proposed volumes (Table 1), while remaining significantly smaller than Salyut, the ISS, and Space Lab. The only potential areas where volume could technically be reduced included the individual crew quarters and the work area; a key mitigation in future spaceflight habitats; however, particularly habitats supporting long-duration missions, is the preservation of the volume of the berthing/crew quarters, and the volume of the dining and communal areas. There may be technological advances (smaller exercise devices) in the future that allow for slight reductions in work, hygiene, and exercise space, but these remain to be developed and tested. Additional consideration is that EVAs may require increased volume with the addition of a specific airlock.

As a result, the panel concluded that unless functional requirements change, the volume will not reduce substantially.

Table 1 – Summary Habitable Volumes of Historical Long-Duration Missions and Proposed NHV for Future Exploration Vehicle

Long Duration Mission	Hab Volume (m ³ /person)	Hab Volume (ft ³ /person)	Maximum Mission Duration
Skylab	120.33	4249.41	84 days
ISS	85.17	3007.75	196 days
Salyut	33.5	1183.04	237 days
Mir	45	1589.16	438 days
Proposed NHV	25	882.87	912 days

Forward Plan for Research and Validation. Follow-on work within the NASA team includes the ongoing development and modification of an integrated research plan (IRP) that outlines specific steps needed to test and validate relevant outcomes (for example, performance, behavioral health, physiological health, privacy, team interactions) within the proposed minimum acceptable NHV number. Additional assessments are needed to evaluate the minimum acceptable NHV number and various design configurations that incorporate behavioral health countermeasures anticipated for exploration class missions. The IRP further defines efforts for testing habitability-related countermeasure effectiveness (virtual worlds, immersive environments). In addition to the ISS, various high-fidelity analogs (Human Exploration Research Analog [HERA], the Russian Institute for Biomedical Problems' [IBMP] Mars 500-day chamber, and Antarctica stations) are being used and/or considered to test, validate, and behaviorally assess NHV design solutions for exploration missions.

Such habitability-related efforts will be primarily depicted in the HRP's IRPs within: (1) the Space Human Factors and Habitability Research Gap, *SHFE-HAB-07: We need design guidelines for acceptable NHV and internal vehicle/habitat design configurations for predetermined mission attributes*, and the Behavioral Health and Performance Research Gaps, (2) *BMed7: We need to identify and validate effective methods for modifying the habitat/vehicle environment to mitigate the psychological and behavioral effects of psychological environmental stressors (e.g., isolation, confinement, reduced sensory stimulation) likely to be experienced in exploration class missions*, (3) *Team 1: We need to understand the key threats, indicators and life cycle of the team for autonomous, long duration and/or distance exploration missions*, and (4) *Sleep 10: We need to identify the spaceflight environmental and mission factors that contribute*

to sleep decrements and circadian misalignment, and their acceptable levels of risk. A copy of the current IRP can be found at <http://humanresearchroadmap.nasa.gov/>.

APPENDIX 1

List of Participants

NHV Subject Matter Experts (SMEs)

- Mathias Basner, MD, PhD – University of Pennsylvania Perelman School of Medicine (MD epidemiologist with experience related to the effects of environmental stressors such as noise, confinement, and isolation on human behavior, sleep, and performance)
- Hugh Broughton, MA (Hons) dip Arch – Hugh Broughton Architects (architect with extensive experience in designing living and working structures in Antarctica and the Arctic, including Halley 6 Research Station)
- Laura Ikuma, PhD – Louisiana State University (extensive experience in industrial ergonomics in relevant settings such as workplace and health care settings)
- Anne Kearney, PhD – Kearney Environmental and University of Washington (environmental psychologist with extensive experience in habitat design)
- Michael Morris, MA – Morris Sato Studio and Columbia University (architect with extensive experience in future space design)

NASA/Contractor NHV Team

- Lauren Leveton, PhD – JSC Behavioral Health and Performance Element Scientist
- Alexandra Whitmire, PhD – Wyle Behavioral Health and Performance Portfolio Scientist
- Diana Arias – Wyle Behavioral Health and Performance Portfolio Manager
- Matt Simon – LaRC Exploration Habitation and JSC Exploration Medical Capability
- Mihriban Whitmore, PhD – JSC Space Human Factors and Habitability Acting Element Scientist
- Sherry Thaxton, PhD – JSC Space Human Factors and Habitability
- Maijinn Chen – JSC Space Human Factors and Habitability
- Ron Archer – JSC Space Human Factors and Habitability
- Eric Kerstman, MD, MPH – JSC Aerospace Medicine Physician/Flight Surgeon, Advanced Technologies for Engineering and Medicine

In addition, the following representatives participated in the NHV consensus session: Walter Sipes, PhD – JSC Psychologist; Laura Bollweg – JSC Behavioral Health and Performance Element Manager; Jason Schneiderman, PhD – Wyle Behavioral Health and Performance Portfolio Scientist; Kristine Ohnesorge – JSC Behavioral Health and Performance Portfolio Manager and Holly Patterson – Wyle Behavioral Health and Performance Portfolio Manager; and Jennifer Rochlis, PhD – JSC Space Human Factors and Habitability Element Manager.

APPENDIX 2

List of Expert Reviewers of Draft Report

- Richard Linnehan, BS, DVM, MPA – NASA Astronaut and liaison to the HRP
- Stanley Love, MS, PhD – NASA Astronaut
- Alex Salam, MD, MS – Concordia Antarctic Station participant

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